

## Searches for high energy solar flares with *Fermi*-LAT

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The *Fermi* Large Area Telescope (LAT) has been surveying the sky in gamma rays from 30 MeV to more than 300 GeV since August 2008. *Fermi* is the only mission able to detect high energy ( $>$  few hundreds MeV) emission from the Sun during the new solar cycle 24: the Solar System Science Group of the *Fermi* team is continuously monitoring high energy emission from the Sun searching for flare events. Preliminary upper limits ( $>$  100 MeV) have been derived for all solar flares detected so far by other missions and experiments (RHESSI, *Fermi* GBM, GOES). Upper limit for flaring Sun emission (integrated over one year of data) has also been derived. Here we present the analysis techniques as well as the details of this search and the preliminary results obtained so far.

### I. INTRODUCTION

*Fermi* was successfully launched from Cape Canaveral on 2008 June 11. It is currently in an almost circular orbit around the Earth at an altitude of 565 km having an inclination of 25.6° and an orbital period of 96 minutes. After an initial period of engineering data taking and on-orbit calibration[1], the observatory was put into a sky-survey mode in August 2008. The observatory has two instruments onboard, the Large Area Telescope (LAT)[2], a pair-conversion gamma-ray detector and tracker (energy range 30 MeV -  $>$  300 GeV) and a Gamma-ray Burst Monitor (GBM), dedicated to the detection of gamma-ray bursts (energy range 8 keV - 40 MeV). The instruments on *Fermi* provide coverage over the energy range measurements from few keV to several hundreds of GeV.

Here we report *Fermi* LAT limits on emission  $>$  100 MeV for the few flares detected by other missions over the past year. Solar flares are the most energetic phenomena that occur within our Solar System. A flare is characterized by the impulsive release of a huge amount of energy, previously stored in the magnetic fields of active regions. During a flare plasma of the solar corona and chromosphere is accelerated and electromagnetic radiation covering the entire spectrum is emitted. The production of  $\gamma$ -rays involves flare-accelerated charged-particle (electrons, protons and heavier nuclei) interactions with the ambient solar atmosphere. Electrons accelerated by the flare, or from the decay of  $\pi^\pm$  secondaries produced by nuclear interactions, yield X and  $\gamma$ -ray bremsstrahlung radiation with a spectrum that extends to the energies of the primary particles. Proton and heavy ion interactions also produce  $\gamma$ -rays through  $\pi^0$  decay, resulting in a spectrum that has a maximum at 68 MeV[3].

The frequency of solar flares follows the 11 year so-

lar activity cycle. Most intense flares occur during the maximum, but intense flares can occur also in the rising and decreasing phases of the cycle. The new solar activity cycle 24 has started at the beginning of year 2008, the maximum is predicted in year 2012. *Fermi* has been launched during the minimum of the solar cycle, so the frequency and the intensity of solar flares will increase throughout most of the mission. If the goal of a 10-year mission life is achieved, *Fermi* will operate for nearly the entire duration of solar cycle 24. During this time, *Fermi* will be the only high-energy observatory ( $>$  few hundreds MeV) to complement several solar missions at lower energies: RHESSI, GOES, SoHO, Coronas.

### II. PREVIOUS OBSERVATIONS

The 2005 January 20 solar flare produced one of the most intense, fastest rising and hardest solar energetic particle events ever observed in space or on the ground.  $\gamma$ -ray measurements of the flare[4][5] revealed what appear to be two separate components of particle acceleration at the Sun: i) an impulsive release lasting  $\sim$  10 min with a power-law index of  $\sim$  3 observed in a compact region on the Sun and, ii) an associated release of much higher energy particles having a spectral index  $\leq$  2.3 interacting at the Sun for about two hours. Pion-decay  $\gamma$ -rays appear to dominate the latter component. Such long-duration high-energy events have been observed before, most notably on 1991 June 11 when the EGRET instrument on CGRO observed  $>$  50 MeV emission for over 8 hours[6]. It is possible that these high-energy components are directly related to the particle events observed in space and on Earth.

*Fermi* will improve our understanding of the mechanisms of the  $\gamma$ -ray emission by solar flares thanks to

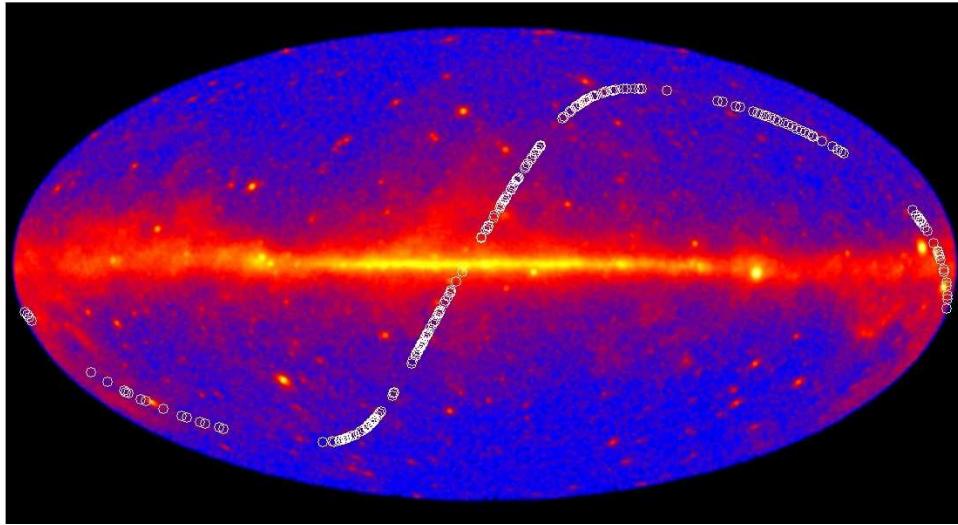


FIG. 1: Solar flares detected by RHESSI and analysed in this search, superimposed on a count map of LAT data ( $E > 200$  MeV) for a easier localization in the sky. There is no evidence of correlation between flare positions and excesses of the LAT events.

its large effective area, sensitivity and high spatial and temporal resolution.

### III. MONITOR OF SOLAR CYCLE 24

The solar cycle 24 has started at the beginning of 2008, but actually we are in an extended period of minimal solar activity. We are seeing an interesting diminished level of activity. There are some discussion ongoing if sunspots and flares ever return and how unusual is this behavior[7]. A closer look at the daily values of three indices: F10.7 (10 cm radio flux from the Sun), the total solar irradiance TSI, and the classical sunspot number give only a little appearance of a up-turn. In the modern era there is no precedent for such a protracted activity minimum, but there are historical records from a century ago of a similar pattern (transition between cycles 13 and 14, 107 years ago).

Activity is expected to pick up in the next months. In the meanwhile is a good opportunity to use the excellent data available from many satellites to improve LAT analysis of solar flares and practise in flare monitoring and analysis, to be ready when the first intense flare of cycle 24 will arrive.

### IV. DATA SELECTION

Since August 2008 flares detected by RHESSI and GOES have been continuously monitored, analysing LAT data for flare events potentially detectable by the LAT and computing upper limits on the solar high energy emission. Solar flares have been searched in LAT

data from Augusr 2008 to the end of August 2009. LAT data have been analysed in the time intervals of flares detected by GBM, RHESSI and GOES. A zenith cut of  $105^\circ$  has been applied to eliminate photons from the Earth's albedo. For this analysis the “Diffuse” class[2] selection has been adopted, corresponding to the events with the highest photon classification probability, using the IRFs (Instrumental Response Functions) version P6\_V3.

### V. ANALYSIS METHOD

The list of flares detected by RHESSI[8] and the *Solar Monitor* web site[9] were monitored constantly at a daily basis. Flares seen by RHESSI and GOES with more than  $10^5$  counts (detected by RHESSI) have been selected. For each of these flares start and end time of the event in *Fermi* MET (Mission Elapsed Time), the position of the Sun during the flare and the angle of the Sun direction with the LAT boresight have been computed.

The excess of events in the LAT data has been searched for flares within the LAT field of view (angle with the LAT boresight  $< 80^\circ$ ). Although the Sun is a moving source in the sky, covering about  $1^\circ$  per day, in this analysis the Sun has been considered as a fixed source, due to the short duration of the flare events ( $< 1$  h). As analysis method a likelihood fitting technique has been used, performed with a model that includes the Sun as a point source and fixed galactic and extragalactic diffuse emission.

Moreover, the upper limit of high energy solar emission integrated on more than one year of flares has been computed. LAT data of flares detected by

RHESSI have been collected (data selected one hour before and five hours later with respect RHESSI flares, because of the long duration of high energy emission). The position of the Sun has been computed using a JPL library interface[10] and then data have been centered on the instantaneous solar position. Successively these data have been merged and the analysis has been performed, using the standard likelihood technique provided by the LAT ScienceTools package (v9r15). Since the Sun is a moving source in the sky, the problem is to compute the correct galactic and extragalactic diffuse background emission as the Sun moves through the sky. In order to evaluate the diffuse background in proper way the fake source method has been used. The fake Sun follows the real Sun along the same path (i.e. the ecliptic) but at an angular distance of  $30^\circ$ . The fake Sun is therefore exposed to the same celestial sources as the true Sun and the events observed in the frame centered on the fake Sun make a good description of the diffuse background. The model for the likelihood analysis is composed by two fixed components (quiet Sun and fake Sun) obtained in previous analysis[11][12][13] and the flaring Sun free component.

## VI. RESULTS

At 20:14:42.77 UT on 02 November 2008, *Fermi*-GBM triggered and located a very soft and bright event[14]. The event location was RA =  $217.6^\circ$ , Dec =  $-15.7^\circ$  ( $\pm 1.1^\circ$  deg), in excellent agreement with the Sun location. The time of the event coincides with the solar activity reported in GOES solar reports (event 9790: onset at 20:12 UT, max at 20:15 UT, end at 20:17, B5.7 flare). This is the first GBM detection of a solar flare. *Fermi*-GBM triggered on a solar flare a second time at 19:37:46.39 UT on 28 October 2009[15]. LAT data have been selected in the energy range 100 MeV - 300 GeV, according to the solar activity detected by GOES and RHESSI: no high energy emission has been detected by the LAT for both events.

From August 2008 to August 2009 RHESSI has detected 200 flares with  $> 10^5$  counts. The highest energy band in which most of these flare have been observed by RHESSI is 3-6 keV. Few flares ( $< 20$ ) have been observed in the energy band 6-12 or 12-25 keV. Flares outside the LAT field of view and the ones that occurred while the LAT was transiting in

the SAA have been discarded. As a result LAT data of 80 flares have been analysed and the upper limit on the high energy ( $> 100$  MeV) emission has been computed for each of these flares. No significant emission has been detected.

The preliminary upper limit on the emission of the flaring Sun integrated over one year of flares in LAT data is  $5.67 \cdot 10^{-7}$  photons  $\text{cm}^{-2} \text{s}^{-1}$ . This value is derived from a cumulative analysis of all the 80 flares with a time of six hour around each trigger time (one hour before and five hours later), taking into account the quiet sun component[16]. A more detailed analysis is in preparation.

## VII. CONCLUSIONS

Solar flare events have been searched in the first year of LAT data (August 2008 - August 2009). Up until now there is no evidence of high energy emission from solar flares detected by the LAT, while the quiet Sun emission has been detected[11][12][13]. However, the Sun is at the minimum of its activity cycle and no intense flare has occurred. The solar activity is expected to rise in the next months, reaching the maximum in 2012.

We will continue to monitor the active regions of the Sun and to improve our analysis techniques, waiting for an intense flare detectable by the LAT.

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